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Evaluating predictors of lead exposure for activities disturbing materials painted with or containing lead using historic published data from U.S. workplaces

Sarah J. Locke¹, Nicole C. Deziel², Dong-Hee Koh³, Barry I. Graubard⁴, Mark P. Purdue¹, and Melissa C. Friesen¹

¹Occupational and Environmental Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, MD, U.S.A.

²Yale School of Public Health, Yale University, New Haven, CT, U.S.A.

³Department of Occupational and Environmental Medicine, International St. Mary's Hospital, Catholic Kwandong University, Incheon, Korea

⁴Biostatistics Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, MD, U.S.A.

Abstract

Objectives—We evaluated predictors of differences in published occupational lead concentrations for activities disturbing material painted with or containing lead in US workplaces to aid historical exposure reconstruction.

Methods—For the aforementioned tasks, 221 air and 113 blood lead summary results (1960–2010) were extracted from a previously developed database. Differences in the natural log-transformed geometric mean (GM) for year, industry, job, and other ancillary variables were evaluated in meta-regression models that weighted each summary result by its inverse variance and sample size.

Results—Air and blood lead GMs declined 5%/year and 6%/year, respectively, in most industries. Exposure contrast in the GMs across the 9 jobs and 5 industries was higher based on air vs. blood concentrations. For welding activities, blood lead GMs were 1.7 times higher in worst-case vs. non-worst case scenarios.

Conclusions—Job, industry, and time-specific exposure differences were identified; other determinants were too sparse or collinear to characterize.

Keywords

Lead; occupational exposure; exposure determinants; meta-regression; population-based studies

Introduction

In population-based studies, exposure assessment approaches have begun to systematically incorporate measurement data to identify determinants of exposure that can be used to anchor exposure intensity estimates (Friesen et al. 2012; Friesen et al. 2014a; Friesen et al. 2014b; Hein et al. 2008; Hein et al. 2010; Peters et al. 2010; Peters et al. 2011). For these efforts the published literature has often been an important measurement source (Friesen et al. 2014b; Hein et al. 2008; Hein et al. 2010; Sauvé et al. 2012, 2013). For example, a statistical model of published metalworking fluid measurements was used to estimate the intensity of straight, soluble, and synthetic metalworking fluid exposure for a case-control study of bladder cancer (Friesen et al. 2014b). The resulting estimates demonstrated a significant increased bladder cancer risk with increasing straight metalworking fluid exposure (Colt et al. 2014) that was consistent with the exposure-response associations observed in an industry cohort study (Friesen et al. 2009).

To aid historical exposure reconstruction efforts in US population-based studies, we previously compiled a database of published occupational lead measurements from U.S. workplaces (Koh et al. 2015). Lead has been widely used in metal alloys, pigments, plastics, rubber, and paints across U.S. industries for many decades (ATSDR 2007), and has been associated with a variety of different adverse health effects that include nervous system, liver and kidney damage and cancer (ATSDR 2007, IARC 2006). Our first evaluations of this lead measurement database identified temporal trends for a variety of industries with published measurements spanning ten or more years that differed by sample type (air vs. blood) (Koh et al. 2014). However, these previous analyses did not examine the effects of job category, some of which may occur in multiple industries, or the influence of other ancillary data, which were sparse for most industries. In this paper, we present more detailed analyses of a subset of this database, focusing on measurements collected from US workers performing activities related to lead-based paint and cutting/joining metal with heat in the presence of lead. These activities are prevalent in the US working population and represented approximately one-third of the published personal air and blood lead summary results in the database (Koh et al. 2015). The jobs performing these activities occur in a variety of industries (e.g., welding, painting). For these activities, our objective was to identify exposure differences by job (or task), industry, and time period, as well as evaluate the influence of other ancillary variables available in the data set. The job-, industry-, and time-specific differences in exposure identified in this systematic evaluation can be used to aid historical exposure reconstruction efforts in population-based studies.

Materials and Methods

The database of occupational lead concentrations in US workplaces reported in the published literature from 1940 through December 31, 2010, was first described in Koh et al. (2015). Relevant studies were identified by searching web-based bibliographic databases (MEDLINE, Web of Science, Scopus, SciFinder, NIOSHTIC2) using the search terms “lead exposure,” “worker,” “occupation,” and “occupational exposure” and by reviewing the identified papers’ citations. The database was constructed from lead measurements that were predominantly reported as summary results (i.e., geometric means (GMs) and geometric

standard deviations (GSDs)). The exposure concentrations and measures of exposure variability were extracted and converted, when necessary, to obtain a GM and GSD for each set of summary results. The three air summary results reported below the limit of detection were replaced with values of 1/2 times the detection limit. Concurrently, ancillary data were extracted on measurement year, sample type (area air, personal air, blood), industry, job, task, particle size fraction, sampling duration, analytic method, containment structure use, lead-based paint removal activities, respirator use, ventilation use, and worst case scenarios (e.g., elevated blood lead levels, employee concerns, regulatory violations). The database contained 525 sets of personal air summary results and 351 sets of blood lead summary results, representing 27 2-digit SIC codes from 175 exposure studies conducted within US workplaces.

For the present analyses, we extracted the subset of personal air and blood lead summary results associated with lead-based paint work or joining or cutting metal in the presence of lead using heat. This subset represented 9 of the 27 2-digit SIC codes and 69 of the 175 exposure studies in the exposure data set. Summary results were categorized into, represented 9 occupation groups and 5 industry groups (Table I) and included automotive repair services, ship building and repair, general and heavy construction, and automotive manufacturing. The complete dataset can be found in Supplementary Table SI. The selected personal summary results included 12 area air summary results because, upon expert review of the original papers, it was determined that these samples were collected in a manner that represented personal exposure. The air measurements were restricted to those where the particle size was inhalable, total suspended particle (collected using a closed-face 37 mm cassette), or not specifically reported (expected to be inhalable or total suspended particle), thus excluding 11 respirable air summary results. We excluded the 15 personal air and 1 blood lead summary results collected pre-1960. For this subset, we categorized industry into five groups and job into nine groups, which are listed in Table I and defined in more detail in online Supplementary Table SI. We assigned a sample size-weighted average GSD of 3.0 and 1.9 for air and blood lead, respectively, to sets of summary results that were comprised of a single measurement (15 air, 6 blood summary results), that had no measure of variability (3 air, 2 blood), or where the GSD equaled 1 (2 air). The weighted average GSDs were calculated using all studies in this subset, except Nelson et al. (1993), which reported AM air summary results with large sample sizes that spanned up to one decade and had extremely wide ranges of exposure. The data in this subset and their corresponding sources are provided in Supplementary Table SI.

We examined predictors of historical lead exposure in this subset separately for air and for blood lead using mixed-effects meta-analysis models using SAS 9.3 (SAS Institute Inc., Cary, NC, USA) based on the framework previously used to characterize temporal trends within this database (Koh et al. 2014). This structure accounts for both within- and between-study variability by incorporating a random-effect that weights each summary result by the inverse of the log-transformed variance divided by the number of measurements. Each model used the natural log-transformed GM (lnGM) as the dependent variable. Ancillary data were incorporated into the models as fixed effects. Regression parameters and between-study variances (starting guess for iterations set to 1/2 times the average within-study variance) were obtained using maximum likelihood estimation.

The complete list of ancillary variables considered in the modeling process are listed in Supplementary Table SII. Prior to inclusion in the model, ancillary variables were examined using cross-tabulations, correlation measures, and univariate models. This eliminated several variables from further consideration because they were not associated with lnGM in univariate models, they were strongly collinear with industry or job, or there were <3 summary results in the response category of interest (sampling duration, analytical methods, containment structure use, lead-based paint removal activities, number of measurements, ventilation use, analytical category). Year was incorporated both as a main effect and as an interaction term with industry because previous evaluations observed industry-specific temporal trends (Koh et al. 2014). Initial evaluations of the worst case variable (industrial hygiene surveys initiated in response to elevated blood lead levels, employee concerns, or regulatory violations) found that worst case scenarios were reported exclusively for two jobs: abrasive blasters and welders/burners/ironworkers. To distinguish these samples from representative samples and to avoid assuming that the variable ‘worst case’ was associated with other jobs and that the magnitude of the effect was the same across the two jobs, we derived two job-specific variables – ‘worst case exposure scenario: abrasive blasters’ and ‘worst case exposure scenario: welders/burners/ironworkers’ – that were coded ‘Yes’ if worst case sample relevant to the given job, ‘No’ if representative sample, and ‘Not Reported’ if not specified

The ancillary variables were evaluated in the models using a backward, manual step-wise approach for each model, removing variables with the highest p-value one at a time until all variables had p-values <0.1. Categorical variables were evaluated as a group. The main effect for year was kept in the model regardless of its p-value because statistically significant industry-year interactions were observed. Because task was strongly collinear with job, a separate set of models was developed by replacing job with task.

Results

The subset of the database pertaining to lead-based paints and cutting and joining metals with heat and meeting our inclusion criteria comprised 221 personal air lead summary results from 47 papers representing 3,931 measurements and 113 blood lead summary results from 45 papers representing 4,783 measurements. Personal air GMs ranged from <1 to over 10,000 $\mu\text{g}/\text{m}^3$ and blood lead GMs ranged from 2.4 to 100 $\mu\text{g}/\text{dL}$. The distribution of these summary results by industry and job is shown in Table I. Worst case exposure scenarios were reported infrequently and were observed only for abrasive blasters (14 air, 1 blood summary results) and welder/burner/ironworkers (6 air, 4 blood summary results).

The model parameters of the air and blood lead summary results for the models that used job, rather than task, are shown in Table I. The independent variables explained 52% of the personal air between-summary result variance and 70% of the blood lead between-summary result variance. The model parameters of the air and blood lead summary results for the models that replaced job with task are shown in Supplementary Table SIII.

The air model using job estimated a non-significant 4.6% decline per year for all industries except shipyard, (Table I, Figure 1). The time trend for shipyards increased 5.1% per year

($\exp(-0.047+0.097)$). Systematic differences in exposure occurred by industry, with the lowest exposures predicted for 'general and residential construction' and the highest for 'shipyards'. Similarly, predicted GMs varied across the 9 occupation groups, with the lowest predicted GMs for 'construction other and maintenance' and the highest for 'abrasive blaster'.

The blood lead model estimated a 6.2% decline per year ($p<0.0001$) for three of the five industries (Table I, Figure 1). Significant industry-year interactions predicted a 2.8% decline per year ($\exp(-0.064+0.036)$) for 'general and residential construction' and 2.2% decline per year ($\exp(-0.064+0.042)$) for 'miscellaneous' industries. For industry, the lowest predicted GMs occurred for 'general and residential construction' and the highest for 'miscellaneous' industries. These time trends are shown graphically in Figure 2. For Occupation, the lowest predicted GMs were observed for 'chipper/grinder/sander' and the highest for 'steel renovation and demolition worker'; however, most jobs were not significantly different from the reference job 'painter'.

Based on these models, predicted GMs and their respective confidence intervals for job-industry combinations that were represented in this subset were calculated and listed in Table II. For air, predicted GMs for the reference year 1990 ranged across an order of magnitude, from a low of $1 \mu\text{g}/\text{m}^3$ for 'renovation and demolition workers' in 'general and residential construction' to a high of $615 \mu\text{g}/\text{m}^3$ for 'abrasive blasters' in 'shipyards'. For blood, the exposure range was much narrower, from a low of $4 \mu\text{g}/\text{dL}$ for 'construction, other and maintenance' in 'general and residential construction' to a high of $30 \mu\text{g}/\text{dL}$ for 'steel renovation/demolition workers' in 'steel structure construction'.

Similar patterns were observed when job was replaced with task (Supplementary Table SIII). In the task models, respirator use was associated with a 3.1 times higher GM of personal air lead concentrations than no respirator use.

Discussion

We used meta-regression models based on published occupational lead concentrations to quantify job-, industry-, and time-specific differences in personal airborne and blood lead exposures for activities related to lead-based paint work and joining or cutting metal using heat to aid historical exposure reconstruction efforts in US population-based studies. These models allowed us to systematically quantify exposure differences while accounting for each summary result's variance and number of measurements. In contrast, previous analyses of the published literature have weighted each summary result only by the number of measurements (Hein et al. 2008; Hein et al. 2010), ignoring measurements' variability, or have derived data sets of individual measurements using simulations (Lavoue et al. 2007; Sauvé et al. 2012, 2013), which is a more complex method for accounting for both the variance and number of measurements.

The temporal trends generally declined more steeply in the models based on blood vs. air summary results (6.2 vs. 4.6% per year for most industries); however, the confidence intervals overlap. Two industry-specific time trends were observed: an increase of 5.1% per

year for ‘shipyards’ based on air concentrations and a more modest decline of 2–3% per year for ‘general and residential construction’ and ‘miscellaneous’ industries based on blood concentrations. The increasing trend for ‘shipyard’ air concentrations may be an artifact of the conditions observed in the latter studies, which included high personal air lead concentrations during lead-based paint removal using abrasive blasting (Jarret et al. 2003) or power tools (Zedd et al. 1993; Mattarano et al. 1999) in confined spaces or containment areas while wearing supply air or air purifying respirators. A comparable increasing shipyard-specific time trend was not observed in the blood lead models, where blood lead declined 6.2% per year, which likely represents the use of respirators during these high airborne exposure activities. The more modest decline in blood lead in ‘general and residential construction’ may be because the US Occupational Safety and Health Administration’s (OSHA) lead in construction standard, which lowered lead occupational exposure limits four-fold, was enacted in 1993 (OSHA 1993), 15 years after OSHA’s General Industry lead standard, which was enacted in 1978 and covered general industry and shipyards (OSHA 1978). These industry- and sample type-differences are generally consistent with our previous temporal evaluations (Koh et al. 2014), but differed slightly because the models evaluated here also accounted for job and included summary results from lead-based paint removal (abatement) activities or from work performed inside containments. Our previous evaluations only included calendar year in the model and excluded measurements for these two scenarios. The observed temporal trends based on lead air measurements were consistent with Creely et al.’s (2007) evaluations of published lead air measurements, which found declines of 1–9% per year, and were lower than the 8–11% declines per year observed in the inspection air measurements collected by the US Occupational Safety and Health Administration (Okun et al. 2004).

The range in industry and job-specific differences in GMs tended to be wider for models based on air vs. blood lead measurements, which is consistent with the generally larger variability in air versus biological measurements that has been demonstrated across a wide variety of agents (Symanski et al. 2007). Air measurements represent only the measured time period and do not account for protective effects of respirators, which are used in many of these environments. In contrast, blood lead, with its half-life of ~30 days, provides a measure of the average, internal lead dose for recent exposure that accounts for the day-to-day variability in air lead concentrations, physiological damping, and personal behaviors, such as hygiene practices and respirator and other protective equipment use (Rappaport and Spear 1988; ACGIH 2001a). Day-to-day variability in airborne lead concentrations can be particularly pronounced in construction industry workers, where the worksite, tasks, and associated exposures change constantly (Ringten et al 2004). In addition, the relationship between air and blood lead levels can vary as a result of particle size, airborne concentrations, incidental ingestion, and personal behaviors (i.e., respirator use), such that the airborne route may not always be the primary route of exposure (ACGIH 2001b; EPA 2006).

Despite a focus on a subset where there was more data and the availability of ancillary data, only year, job, and industry were the main predictors of exposure. One ancillary variable -- worst-case scenarios for ‘welder/burner/ironworker’ jobs -- remained as a significant predictor and only in the model based on blood lead concentrations. The 1.7 times higher

predicted GMs for worst case exposure scenarios for welder/burner/ironworkers compared to 'representative' scenarios based on blood models is not surprising as these measurements were collected in targeted circumstances that likely represent atypical exposure scenarios. This pattern is consistent with the 1.8 times higher silica GMs observed for worst case scenarios in a compiled database of airborne respirable crystalline silica measurements (Peters et al. 2011), but was less than the five-fold increased GMs for worst case scenarios of airborne bitumen fume exposure in asphalt pavers (Burstyn et al. 2000b). No differences were observed for worst case abrasive blasters, perhaps due to small numbers. In addition, in the models where task replaced job (Supplemental Table SIII), respirator use was associated with 3 times higher air lead levels than when no respirators were used, which is not surprising because activities with known elevated air lead levels generally necessitate respirator use. Respirator use was not a predictor of exposure in the air model using job, possibly because a given job may perform multiple tasks, some requiring the use of respirators and others not.

There were several limitations to our evaluations. First, we were able to capture exposure differences for the primary occupational characteristics available in epidemiologic studies – job, industry, and time period – but we were unable to identify task-specific differences within jobs or other determinants of exposure because the ancillary variables were highly collinear or were too sparse to evaluate. Collinearity and sparse data have also limited other exposure modeling efforts (Burstyn et al. 2000a; Flanagan et al. 2006; Friesen et al. 2014b; Gold et al. 2008; Hein et al. 2008; Hein et al. 2010; Sauvé et al. 2013). Second, our evaluations assume that these studies are a random sample from an 'average' US workplace. However, the data may be a mixture of both 'best case' scenarios, with good control measures, and 'worst case' scenarios, where measurements were allowed because of health concerns among employees. In addition, the measurements were concentrated within several job-industry combinations. The application of these models will need to consider whether the concentrations reported for these combinations are representative of typical exposure scenarios and will need to be cautious when extrapolating beyond the observed combinations. Third, we modelled the GM rather than the AM because of the statistical properties of log-normally distributed data. Directly predicting arithmetic means, while weighting each result by its variance, would require non-linear and more flexible modeling approaches. However, the arithmetic mean (AM) can be approximated using the equation $AM = \exp(\ln GM + 0.5 * SE^2)$. Fourth, other publicly available data (e.g., NIOSH Health Hazard Evaluations) were not yet included because of the time-consuming nature of extracting data. The modeling framework used here is flexible and the results can be updated as more data are extracted.

An additional limitation is that neither the air nor blood models disentangle exposures from disturbing materials painted with or containing lead from exposure to leaded gasoline vehicle emissions. Exposure to leaded gasoline emissions has occurred occupationally in most of the occupations, thus these models should be interpreted as representing the median occupational exposure for all lead sources for these jobs and industries. Some environmental exposure to leaded gasoline emissions may also be included in the blood lead measurements from commuting and hobby activities; however, since the EPA's 1975 mandatory phasedown of lead's use as a fuel additive for on-road vehicles, and its eventual ban in 1995,

environmental exposure in these activities is likely to be nominal in comparison to their occupational exposures. For comparison, the predicted blood lead levels reported here by industry (Figure 2) generally exceeded the overall blood lead GMs for US adults, based on data from National Health and Nutrition Examination Surveys, which was 13.1 µg/dL in 1976–1980, 3.0 µg/dL in 1988–1991, (Pirkle et al 1994), and 1.2 µg/dL in 2009–2010 (CDC 2013). In addition, these population levels include both occupational and environmental exposure to lead.

To aid exposure reconstruction efforts, we provided the predicted GMs (and confidence intervals) for the model reference year 1990 using both the air and blood models for job-industry combinations that were represented in the data subset. These values and the identified time trends can be used as a starting point to anchor exposure intensity estimates in population-based studies, which require characterizing exposure differences across a wide range of exposed occupations and industries over several decades. Predicted GMs were not calculated for missing combinations so that gaps in data were readily identifiable. Some of these gaps occurred because the job was only relevant for a subset of the industries. For example, summary results for ‘auto radiator repairer’ were only found for the ‘autobody and radiator repair’ industry. Other gaps represented gaps in the literature. For example, no air or blood air measurements were found in the data set for ‘painters’ in the ‘shipyard’ industry. We also denoted the years for which measurements were available. These values represent a starting point that other researchers may use in the developing of retrospective population-level exposure estimates. Extrapolating exposure estimates for gaps in the data, or beyond the years of coverage, will require additional efforts, such as expert judgment or obtaining other exposure data sources for the jobs, industries, and years represented in their studies. Similarly, researchers may choose to use this modeling framework to conduct additional analyses of this lead database, focusing on the occupations and industries relevant to their study population, or to use this modeling framework on an expanded exposure database that includes other data sources and countries.

In conclusion, published measurements from US workplaces allowed us to systematically characterize time-, industry-, and job-differences in occupational lead exposure for some of the most prevalent lead exposed activities – activities related to lead-based paint and cutting and joining metal. This allowed us to obtain an approximation of an ‘average’ exposure for these activities in US workplaces that can be used in future exposure assessment efforts in population-based studies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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References

- ACGIH. Lead and inorganic compounds BEI. In: ACGIH. , editor. Documentation of Threshold Limit Values and Biological Exposure Indices. Cincinnati, OH: ACGIH; 2001a.
- ACGIH. Lead and inorganic compounds. In: ACGIH. , editor. Documentation of Threshold Limit Values and Biological Exposure Indices. Cincinnati, OH: ACGIH; 2001b.
- ATSDR. Toxicological Profile for Lead. Atlanta, Georgia: US Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry; 2006. p. 582
- Burstyn I, Kromhout H, Boffetta P. Literature review of levels and determinants of exposure to potential carcinogens and other agents in the road construction industry. *AIHAJ*. 2000a; 61:715–726. [PubMed: 11071424]
- Burstyn I, Kromhout H, Kauppinen T, Heikkila P, Boffetta P. Statistical modelling of the determinants of historical exposure to bitumen and polycyclic aromatic hydrocarbons among paving workers. *Ann OccHyg*. 2000b; 44:43–56.
- CDC. [accessed 04/2016] Centers for Disease Control and Prevention Fourth National Exposure Report. 2013. Updated Tables, September 2013, http://www.cdc.gov/exposurereport/pdf/fourthreport_updatedTables_sep2013.pdf
- Colt JS, Friesen MC, Stewart PA, Donguk P, Johnson A, Schwenn M, et al. A case-control study of occupational exposure to metalworking fluids and bladder cancer risk among men. *Occ Environ Med*. 2014; 71:667–674.
- Creely KS, Cowie H, Tongeren M, Kromhout H, Tickner J, Cherrie JW. Trends in inhalation exposure--a review of the data in the published scientific literature. *Ann Occup Hyg*. 2007; 51:665–678. [PubMed: 17932083]
- EPA. EPA/600/R-5/144aF. Research Triangle Park, NC: 2006. Air Quality Criteria for Lead.
- Flanagan ME, Seixas N, Becker P, Takacs B, Camp J. Silica exposure on construction sites: Results of an exposure monitoring data compilation project. *J Occup Environ Hyg*. 2006; 3:144–152. [PubMed: 16464818]
- Friesen MC, Costello S, Eisen EA. Quantitative exposure to metalworking fluids and bladder cancer incidence in a cohort of autoworkers. *Am J Epidemiol*. 2009; 169:1471–1478. [PubMed: 19414495]
- Friesen MC, Coble JB, Lu W, Shu XO, Ji BT, Xue SZ, et al. Combining a job-exposure matrix with exposure measurements to assess occupational exposure to benzene in a population cohort in Shanghai, China. *Ann Occ Hyg*. 2012; 56:80–91.
- Friesen MC, Locke SJ, Tornow C, Chen YC, Koh DH, Stewart PA, et al. Systematically extracting metal- and solvent-related occupational information from free-text responses to lifetime occupational history questionnaires. *Ann Occ Hyg*. 2014a; 58:612–624.
- Friesen MC, Park DU, Colt JS, Baris D, Schwenn M, Karagas MR, et al. Developing estimates of frequency and intensity of exposure to three types of metalworking fluids in a population-based case-control study of bladder cancer. *Am J Ind Med*. 2014b; 57:915–927. [PubMed: 25060071]
- Gold LS, De Roos AJ, Waters M, Stewart P. Systematic literature review of uses and levels of occupational exposure to tetrachloroethylene. *J Occup Environ Hyg*. 2008; 5:807–839. [PubMed: 18949603]
- Hein MJ, Waters MA, van Wijngaarden E, Deddens JA, Stewart PA. Issues when modeling benzene, toluene, and xylene exposures using a literature database. *J Occup Environ Hyg*. 2008; 5:36–47. [PubMed: 18041643]
- Hein MJ, Waters MA, Ruder AM, Stenzel MR, Blair A, Stewart PA. Statistical modeling of occupational chlorinated solvent exposures for case-control studies using a literature-based database. *Ann Occ Hyg*. 2010; 54:459–472.
- IARC. Inorganic and organic lead compounds. Lyon, France: International Agency for Research on Cancer; 2006.
- Jarrett C. Evaluation of elevated blood lead in a commercial painter. *Appl Occup Environ Hyg*. 2003; 18:808–811. [PubMed: 14555430]

- Koh DH, Nam JM, Graubard BI, Chen YC, Locke SJ, Friesen MC. Evaluating temporal trends from occupational lead exposure data reported in the published literature using meta-regression. *Ann Occ Hyg.* 2014; 58:1111–1125.
- Koh DH, Locke SJ, Chen YC, Purdue MP, Friesen MC. Lead exposure in us worksites: A literature review and development of an occupational lead exposure database from the published literature. *Am J Ind Med.* 2015; 58:605–616. [PubMed: 25968240]
- Lavoue J, Begin D, Beaudry C, Gerin M. Monte carlo simulation to reconstruct formaldehyde exposure levels from summary parameters reported in the literature. *Ann Occ Hyg.* 2007; 51:161–172.
- Mattorano D, Harney J, Cook C, Roegner K. Metal exposure during ship repair and shipbreaking procedures. *Appl Occup Environ Hyg.* 2001; 16:339–349. [PubMed: 11297046]
- Nelson NA, Robins TG, Garrison RP, Schuman M, White RF. Historical characterization of exposure to mixed solvents for an epidemiologic study of automotive assembly plant workers. *Appl Occup Environ Hyg.* 1993; 8:693–702.
- Okun A, Cooper G, Bailer AJ, Bena J, Stayner L. Trends in occupational lead exposure since the 1978 OSHA lead standard. *Am J Ind Med.* 2004; 45:558–572. [PubMed: 15164400]
- OSHA. [accessed March 25, 2014] 29 cfr 1910. 1025, Occupational Safety and Health Standards, Toxics and Hazardous Substances, lead. 1978. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=10030
- OSHA. [accessed March 25, 2014] 29 cfr 1926.62, Safety and Health Regulations for Construction, Lead. 1993. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10641
- Peters S, Vermeulen R, Cassidy A, t'Mannetje A, van Tongeren M, Boffetta P, et al. Comparison of exposure assessment methods for occupational carcinogens in a multi-centre lung cancer case-control study. *Occ Environ Med.* 2010; 68:148–153.
- Peters S, Vermeulen R, Portengen L, Olsson A, Kendzia B, Vincent R, et al. Modelling of occupational respirable crystalline silica exposure for quantitative exposure assessment in community-based case-control studies. *J Environ Monit.* 2011; 13:3262–3268. [PubMed: 22001827]
- Pirkle JL, Brody DJ, Gunter EW, Kramer RA, Paschal DC, Flegal KM, et al. The decline in blood lead levels in the United-States - The National Health and Nutrition Examination Surveys (NHANES). *JAMA.* 1994; 272:284–291. [PubMed: 8028141]
- Rappaport SM, Spear RC. Physiological damping of exposure variability during brief periods. *Ann Occup Hyg.* 1988; 32:21–33. [PubMed: 3369792]
- Ringen K, Seegal J, Englund A. Safety and Health in the Construction Industry. *Annu Rev Public Health.* 1995; 16:165–188. [PubMed: 7639869]
- Sauvé J-F, Beaudry C, Bégin D, Dion C, Gérin M, Lavoué J. Statistical modeling of crystalline silica exposure by trade in the construction industry using a database compiled from the literature. *J Environ Monit.* 2012; 14:2512–2520. [PubMed: 22875042]
- Sauvé J-F, Beaudry C, Bégin D, Dion C, Gérin M, Lavoué J. Silica exposure during construction activities: Statistical modeling of task-based measurements from the literature. *Ann Occ Hyg.* 2013; 57:432–443.
- Symanski E, Greeson NMH, Chan WY. Evaluating measurement error in estimates of worker exposure assessed in parallel by personal and biological monitoring. *Am J Ind Med.* 2007; 50:112–121. [PubMed: 17238141]
- Virji MA, Woskie SR, Pepper LD. Task-based lead exposures and work site characteristics of bridge surface preparation and painting contractors. *J Occup Environ Hyg.* 2009; 6:99–112. [PubMed: 19065390]
- Zedd HC, Walker YP, Hernandez JE, Thomas RJ. Lead exposures during shipboard chipping and grinding paint-removal operations. *AIHAJ.* 1993; 54:392–396.

Figure 1. shows the predicted industry-based time trends (solid lines) from the personal air mixed effects meta-regression model. Each circle's radius indicates the weight of the summary result (inverse of the squared log-transformed geometric standard deviation (GSD) divided by the number of measurements), with a larger radius representing less weight due to a larger variance and/or small number of measurements.

Figure 2. shows the predicted industry-based time trends (solid lines) from the blood mixed effects meta-regression model. Each circle's radius indicates the weight of the summary result (inverse of the squared log-transformed geometric standard deviation (GSD) divided by the number of measurements), with a larger radius representing less weight due to a larger variance and/or small number of measurements.

Personal air and blood lead models' parameter estimates from mixed-effects meta-regression models of log-transformed (base e) airborne personal lead and blood lead geometric means.

Table 1

Parameters ^a	Personal air lead ^b				Blood lead ^c			
	N Summary Results	β	SE	exp(β)	N Summary Results	β	SE	exp(β)
Intercept		2.87	0.480	18		2.18	0.20	8.8
Year-1990	221	-0.047	0.030	0.95	113	-0.064	0.0086	0.94
(Year-1990)*Shipyard industry	50	0.097	0.043	1.10	-	-	-	-
(Year-1990)*General and residential construction industry ^d	38	-	-	-	13	0.036	0.018	1.04
(Year-1990)*Miscellaneous industries	17	-	-	-	15	0.042	0.020	1.04
Industry								
General and residential construction ^d	38	Ref.		1.0	13	Ref.		1.0
Autobody and radiator repair	22	0.94	1.2	2.5	20	1.1	0.34	2.9
Shipyards	50	2.0	0.66	7.6	20	0.55	0.24	1.7
Steel structure construction	94	1.9	0.53	6.4	45	0.98	0.21	2.7
Miscellaneous industries	17	0.54	0.72	1.7	15	1.4	0.24	4.0
Job								
Painter	31	Ref.		1.0	11	Ref.		1.0
Abrasive blaster	34	1.5	0.51	4.5	9	-0.0017	0.25	1.0
Auto radiator repairer	18	-0.068	1.3	0.93	13	-0.20	0.40	0.82
Chipper/grinder/sander	25	-0.99	0.61	0.37	10	-0.90	0.30	0.41
Construction other and maintenance	12	-4.0	0.69	0.019	12	-0.74	0.24	0.48
Renovation and demolition worker	21	-0.46	0.61	0.63	3	-0.15	0.35	0.86
Steel renovation/demolition worker	12	-0.28	0.60	0.75	6	0.25	0.27	1.3
Welder/burner/ironworker	54	1.4	0.44	4.0	29	-0.19	0.21	0.83
Miscellaneous	14	-0.57	0.70	0.57	20	-0.47	0.24	0.63
Worst case exposure scenario-welder								
No	101	Ref.		1.0	55	Ref.		1.0
Yes	6	n.s.	n.s.	n.s.	4	0.53	0.31	1.7

Parameters ^a	Personal air lead ^b				Blood lead ^c			
	N Summary Results	β	SE	exp(β)	N Summary Results	β	SE	exp(β)
Not reported	114	n.s.	n.s.	n.s.	54	-0.21	0.14	0.81
Between-summary result variance								
Above model		2.93	0.30			0.24	0.04	
Null model (no predictor variables)		6.14	0.61			0.79	0.11	
% variance explained		52%				70%		

β , estimate; SE, standard error; n.s., not significant at p-value <0.1; Ref., reference group.

^aVariables tested in the models and dropped because p-value >0.1: year* autobody and radiator repair, year*miscellaneous industries, respirator use, and worst case exposure scenario-abrasive blaster.

^bPredicted personal air GM of the GMs in the literature = $\exp(\beta_{\text{intercept}}) \times \exp(\beta_{\text{year}})^{\text{year} - 1990} \times (\exp(\beta_{\text{year} * \text{ind}})^{\text{year} - 1990} \times \exp(\beta_{\text{industry}}) \times \exp(\beta_{\text{job}}))$.

^cPredicted blood lead GM of the GMs in the literature = $\exp(\beta_{\text{intercept}}) \times \exp(\beta_{\text{year}})^{\text{year} - 1990} \times (\exp(\beta_{\text{year} * \text{ind}})^{\text{year} - 1990} \times \exp(\beta_{\text{industry}}) \times \exp(\beta_{\text{job}}) \times \exp(\beta_{\text{worst case-welder}}))$.

^dGeneral and residential construction industry had no measurements prior to 1990, so extrapolations of the time trend before 1990 should be made cautiously.

Table II

Predicted geometric means and 95% confidence intervals of personal air lead and blood lead concentrations job and industry for the year 1990.

Sample Type Job (time span of measurements taken)	Predicted GM (air: $\mu\text{g}/\text{m}^3$; blood: $\mu\text{g}/\text{dL}$), by industry											
	General and residential construction			Autobody and radiator repair			Shipyards			Steel structure construction		
	N	GM (CI)	N	GM (CI)	N	GM (CI)	N	GM (CI)	N	GM (CI)	N	GM (CI)
Air												
Painter (1980–1996)	11	18 (7–46)	-	n.c.	-	n.c.	19	113 (55–231)	1	30 (9–99)	-	-
Abrasive blaster (1980–2004)	-	n.c.	-	n.c.	13	615 (261–1451)	21	514 (254–1040)	-	n.c.	-	-
Auto radiator repairer (1979–1994)	-	n.c.	18	42 (20–87)	-	n.c.	-	n.c.	-	n.c.	-	n.c.
Chipper/grinder/sander (1986–2002)	1	7 (2–29)	-	n.c.	22	50 (24–104)	2	42 (16–113)	-	n.c.	-	-
Construction other and maintenance (1986–2000)	-	n.c.	-	n.c.	3	3 (1–10)	3	2 (1–7)	6	1 (0–3)	-	-
Renovation and demolition worker (1990–2000)	21	1 (0–2)	-	n.c.	-	n.c.	-	n.c.	-	n.c.	-	n.c.
Steel renovation/demolition worker (1980–1999)	3	13 (4–47)	-	n.c.	-	n.c.	9	85 (30–238)	-	n.c.	-	-
Welder/burner/Ironworker (1963–2004)	2	7 (2–22)	-	n.c.	10	546 (252–1184)	35	456 (269–773)	7	122 (46–322)	-	-
Miscellaneous (1980–2002)	-	n.c.	4	25 (4–162)	2	77 (21–281)	5	64 (20–210)	3	17 (5–62)	-	-
Blood												
Painter (1962–2002)	4	9 (6–13)	1	25 (12–51)	-	n.c.	6	23 (15–35)	-	n.c.	-	-
Abrasive blaster (1980–1994)	1	9 (5–15)	0	n.c.	-	n.c.	8	23 (15–34)	-	n.c.	-	-
Auto radiator repairer (1979–1994)	-	n.c.	13	21 (16–27)	-	n.c.	-	n.c.	-	n.c.	-	-
Chipper/grinder/sander (1966–1991)	-	n.c.	-	n.c.	9	6 (4–8)	1	10 (6–16)	-	n.c.	-	-
Construction other and maintenance (1984–2002)	2	4 (3–6)	-	n.c.	5	7 (5–10)	3	11 (7–16)	2	17 (11–26)	-	-

Sample Type Job (time span of measurements taken)	Predicted GM (air: $\mu\text{g}/\text{m}^3$; blood: g/dL), by industry											
	General and residential construction			Autobody and radiator repair			Shipyards			Steel structure construction		
	N	GM (CI)		N	GM (CI)		N	GM (CI)		N	GM (CI)	
Renovation and demolition worker (1991–1995)	3	8 (5–14)		-	n.c.		-	n.c.		-	n.c.	
Steel renovation/demolition worker (1975–1995)	-	n.c.		-	n.c.		-	n.c.		6	30 (19–46)	
Welder/burner/ironworker (1963–2004)	1	7 (5–11)		-	n.c.		4	13 (9–19)		19	19 (13–27)	
Miscellaneous (1975–2005)	2	6 (4–9)		6	16 (9–27)		2	10 (7–15)		2	15 (10–22)	
										8	22 (16–31)	

CI, 95% confidence interval; GM, geometric mean; N, summary results; n.c., not calculated because no summary results were available for this combination of occupation/industry.